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Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation

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Abstract

Urbanization of watersheds previously managed for agricultural uses results in hydrologic changes associated with increased flooding and erosion. Few studies have been conducted to quantify these effects under controlled conditions and standard rainfall simulation methodologies have not been previously established. In this study, a laboratory rainfall simulation procedure was developed and utilized to evaluate hydrologic and sheet erosional responses to various configurations of impervious surface cover at the small scale. Runoff and sediment losses from a sloped (5%) cascade of soil boxes having 50% impervious cover located at the top of the slope or at the bottom of the slope, or having 0% impervious cover were measured. Results indicate that the 50% upslope impervious treatment generated sediment at 3–5 times the rate of the 50% downslope impervious treatment. Upslope impervious cover resulted in initially lower water runoff rates than channel development, but this effect narrowed or reversed with continued rainfall. These results suggest that upslope impervious surfaces may represent a larger total on-site erosion risk than equivalent impervious surfaces located at lower positions along the slope, especially under high antecedent soil moisture and/or high intensity rainfall.

Keywords: Impervious surface; Watershed; Hydrology; Urbanization; Land use

1. Introduction

The current socioeconomic climate favors the conversion of land previously in agricultural management for urban and suburban uses. As agricultural watersheds are urbanized, the resultant increase in impervious rooftops and transportation surfaces becomes a major controlling factor of the new urban watershed hydrology. In particular, the addition of impervious cover increases the overall hydraulic efficiency of a catchment (Putnam, 1972; Johnson and Sayre, 1973). Precipitation that falls on rooftops and pavement quickly runs off, instead of infiltrating into the soil as it would generally do in a natural or farmed landscape. This shift in the landscape setting typically leads to increased runoff volume and peak flow rates (Moscrip and Montgomery, 1997) and subsequent increased magnitude and frequency of local flooding (Field et al., 1982), soil erosion (Doyle et al., 2000) and contaminant transport (Schueler, 1995; USEPA, 2001), and a decrease in time of concentration (Sauer et al., 1983). One study found a nearly 50% increase in sediment yield after urban development (Nelson and Booth, 2002), due mainly to altered watershed hydrology. The economic and environmental impacts of the resulting damage to property and ecosystems are significant (Booth and Jackson, 1997; Novotny et al., 2001).

While altered hydrology and increased erosion are a known result of urbanization, impacts of the extent and spatial distributions of impervious elements are not well understood (Shuster et al., 2005). Different methods that have been previously used to estimate runoff (e.g. TR55, NRCS) for impervious areas and for even small watershed with some percentage impervious area yield highly inconsistent estimates and this diminished reliability may be attributed to lack of accounting for spatial distribution of impervious cover (Pandit and Regan, 1998). Previous research indicates that impervious distance from, as well as hydraulic connectedness to, the main

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Table 1
Experimental treatment slope surface composition

Impervious treatment	Upslope Box 1	Box 2	Box 3	Downslope Box 4
Upslope	I	I	S	S
Downslope	S	S	I	I
None	S	S	S	S

I = impervious surface; S = soil surface.

channel or tributaries are important in predicting stream and biotic changes associated with urbanization (Lammert and Allan, 1999; Wang et al., 2001; Lee and Heaney, 2003). As part of this study, modular serial soil box laboratory rainfall simulation methods sensitive to the spatial distribution of impervious cover were developed. The primary objectives of this study were to determine the hydrologic and erosional impacts due to the replacement of pervious soil surfaces with impervious cover arranged on the upslope or downslope along a one-dimensional slope under small-scale sheet erosion conditions.

2. Materials and methods

2.1. Treatments

Runoff and sediment losses from sloped plots were measured. Each plot consisted of four segments of 1 m length, having either a soil surface (S) or impervious cover (I). Runoff and sediment losses from plots having impervious cover located at the top of the slope were compared to plots having impervious cover at the bottom of the slope. Treatments are described in Table 1. Each configuration was tested at the 50% impervious level (IISS and SSII). Additionally, similar undeveloped (0% impervious) sloped plots (SSSS) were tested. Three replications of each treatment were performed under two different initial soil moisture content levels: dry (D) (15% < θ_{vi} < 17%), and wet (W) (20% < θ_{vi} < 24%).

2.2. Experimental apparatus

A cascade of four sloped soil boxes was used for rainfall simulations. Each soil box was assigned an S or I designation and then appropriately either filled with a moderately well drained Oxyaquic Dystrudept (silt loam) soil obtained from the North Appalachian Experimental Watershed (Coshocton, OH), or fitted with impervious cover consisting of sheet metal coated with spray-on truck bed liner in order to shed water similarly to smooth asphalt. Soil box layout can be observed in Fig. 1. Each soil box was 1 m long, 60 cm wide, and 20 cm deep (soil depth). Boxes were arranged on a 5% slope so that runoff and sediment flowed from upslope soil boxes into downslope soil boxes through short baffled flumes in the connected position, while hinged interbox sampling devices allowed intermittent sampling of runoff and sediment from each of four individual boxes. Soil was allowed to free drain through holes in the bottom of the soil boxes.

Prior to each rainfall event, soil boxes were prepared by drying soil to an average volumetric moisture content of 16%, sieving to ≤2 cm, and packing each box to a bulk density of 1.25 g/cm^3. The soil cover was then graded with a hand trowel. In order to minimize effects from variability in surface packing, a prewetting rain of 10 mm h^{-1} for a duration of 45 min was applied and the soil boxes were then left to equilibrate for 24 h. Average prepared initial volumetric soil moisture was 16% for D treatments. Without further surface manipulation or preparation, rainfall simulations were repeated for W treatments 72 h after D treatment rainfall simulations were completed. Average prepared initial volumetric soil moisture content was 22% for W treatments. Soil moisture was measured by specific capacitance probes installed horizontally in each box at the 7 cm and 13 cm depths. Measurements were recorded hourly before and after

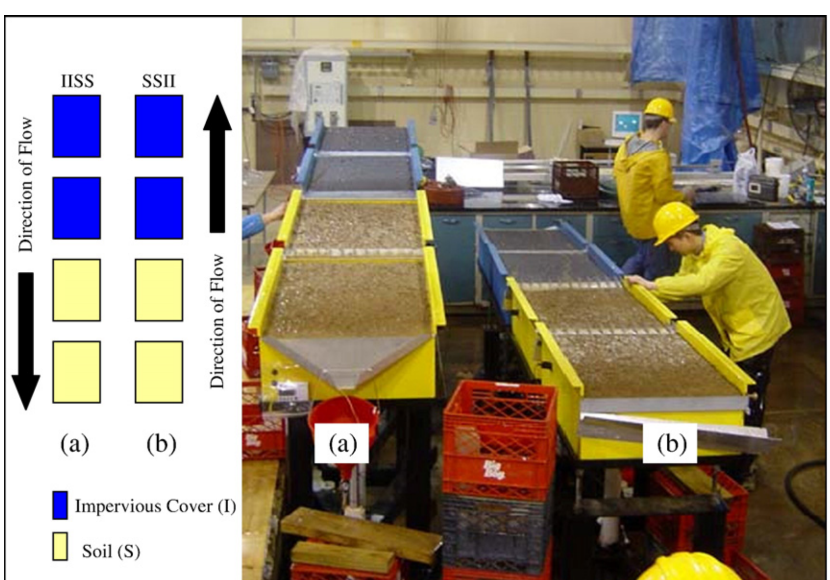

Fig. 1. Serial soil box rainfall simulation representing 50% peripheral impervious surface (a) and 50% channel – located impervious surface (b).

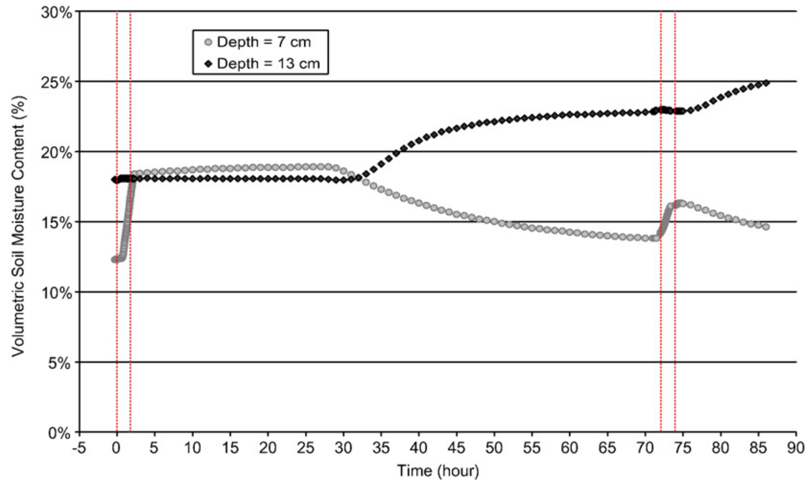

Fig. 2. A soil moisture response curve over the time period including both the dry rainfall simulation (D) and the wet rainfall simulation (W).

rainfall simulations and every 2 min during rainfall simulation. A typical soil moisture response curve is given in Fig. 2.

2.3. Rainfall simulation

A programmable oscillating nozzle rainfall simulator (Foster et al., 1979) was used to generate desired rainfall patterns for all trials. Vertical distance between the nozzles and the soil cover was approximately 2.5 m, and nozzle pressure was 41.4 kPa. The water source was deionized. Rainfall was applied at 20 mm/h for 48 min, then 30 mm/h for 24 min, and 40 mm h^{-1} for 24 min, representing a storm of 96-min duration having an approximate 5-yr return period for the North Appalachian soil borrow site. Rainfall sequence was based on preliminary trials and designed to generate runoff at several rates and reach steady state at multiple rainfall intensities.

Every four minutes, timed 1-min runoff samples were collected in 1-L Nalgene bottles from the entire slope length with all 4 boxes in the connected position. In order to verify uniform box hydrology, drainage water was monitored and timed 1-min runoff samples were collected between boxes and from the remaining plot length every 4 min staggered on a rotation, such that each intermediate box and the remaining downslope plot length was simultaneously sampled every 12 min. A 30-s equilibration period occurred after interbox samplers were opened and before intermediate and remainder sampling and after interbox samplers were closed and before sampling from the entire plot connected. An adjustment factor was developed to account for differences in sediment loss rates caused by the mechanics of the interbox samplers during the equilibration period. The impact was found to be a log function of runoff rate, but was negligible.

2.4. Sample processing

Samples and container tare weights were recorded to the nearest 0.01 g. Then 3–5 mL of saturated alum solution ($AlK(SO_4)_2$) was added to each sample to flocculate suspended sediment. After a 12–18-h settling period at room temperature, samples were decanted and dried at 105 °C to a constant weight.

2.5. Calculations

Runoff volumes were determined for each sample by gravimetric methods using the difference between the weight of the total sample and the weight of the dried bottle and sediment. Runoff and sedimentation rates were determined for each sample interval by dividing respective weights by the sampling duration. Sediment loss flux was calculated in order to compare sediment loss rates from erodible areas of different size, by dividing sediment rates by the soil surface area (1.2 m^2 for impervious treatments, and 2.4 m^2 for soil-only treatments). All statistical analyses were performed using SAS 9.1 (SAS Institute Inc., Cary, and N.C), and non-normally distributed data were log-transformed according to Neter et al. (1996). Significant differences were determined using PROC GLM with $P \leq 0.05$.

3. Results and discussion

3.1. Treatment impacts on hydrology

3.1.1. Initial soil moisture condition impacts on hydrology

As illustrated in Figs. 3 and 4, average runoff time to initiation, time to steady state, and rate were regulated in the early term by both impervious treatment and antecedent soil water status. Overall, more runoff was produced from the W than D treatments. We anticipated this response since soil media will infiltrate at a rate that decreases with increasing soil water content and concomitant decrease in available soil water storage capacity, leading to runoff production (Terstriep et al., 1976). Once this decrease in infiltration rate occurred within soil boxes, steady state runoff was achieved more rapidly (Figs. 3 and 4), and hydrologic differences between soil and impervious treatments were minimal. It can be seen in Fig. 3 that the non-impervious treatment failed to reach steady state runoff during the first rainfall segment (0–48 min) under dry initial soil moisture conditions, but reached steady state by 32 min under wet initial conditions. Under wet initial conditions and 40 mm h^{-1} rainfall intensity, runoff production approached rainfall rate. In the case of channel-located imperviousness, runoff rate exceeded rainfall intensity,

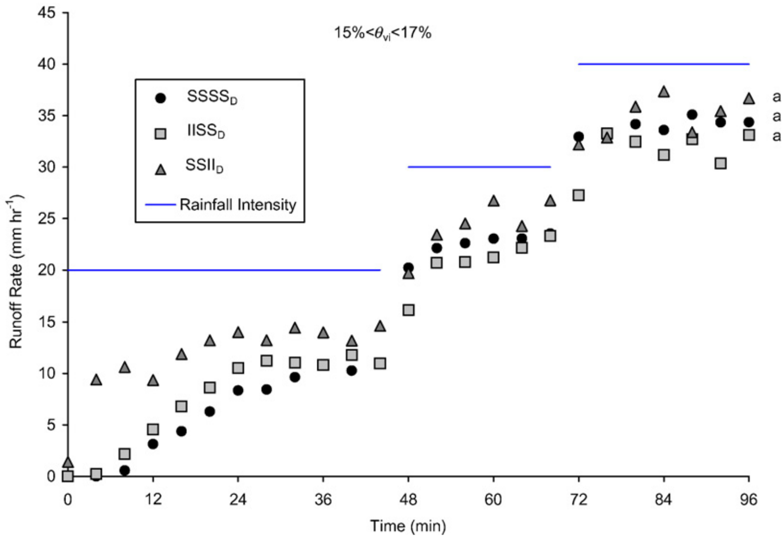

Fig. 3. Runoff rates during simulated rainfall under low initial soil moisture conditions (θ_{vi}). Ending runoff values labeled with the same lower case letter are not significantly different at $\alpha = 0.05$.

suggesting that saturation excess had been reached and some degree of exfiltration had occurred (Fig. 4). Measured soil water content approached saturated water content (41%) during the latter phase of W simulations. Average onset of runoff from $IISS_D$ plots occurred at approximately 8 min, and reached steady state at 28 min, while runoff onset from $IISS_W$ plots occurred between 2 and 4 min after rainfall initiation, and reached steady state at 16 min.

3.1.2. Impervious configuration impacts on hydrology

While impervious surfaces are considered to have some finite storage capacity, largely a function of impervious surface roughness and condition (Albrecht, 1974), impervious water storage capacity was quite small in this experiment. Runoff was produced during the first sampling period, which started at rainfall initiation and ended 2 min later after 0.7 mm of rainfall had been applied. Runoff produced by $SSII_D$ and $SSII_W$ slopes reached steady state after 20 min (6.7 mm), and after 16 min (5.3 mm) of rainfall, respectively. Where infiltration opportunities were maximized (SSSS), runoff rates were initially lower and took longer to reach steady state than any of the impervious treatments, but similar thereafter.

The SSII impervious treatment, having impervious elements in the downslope position, initially delivered runoff more quickly and in greater amounts than when soil occupied the downslope position. This effect can be seen clearly in Fig. 3, where notably higher runoff production can be observed from $SSII_D$ slopes than other treatments prior to steady state. Since impervious surfaces have no significant capacity for abstraction or storage and generate runoff quickly at rainfall initiation, runoff from directly connected impervious surfaces will reach the slope outlet more rapidly than where impervious surfaces run off onto areas having significant capacity for abstraction or storage. In contrast, runoff generated on upslope impervious

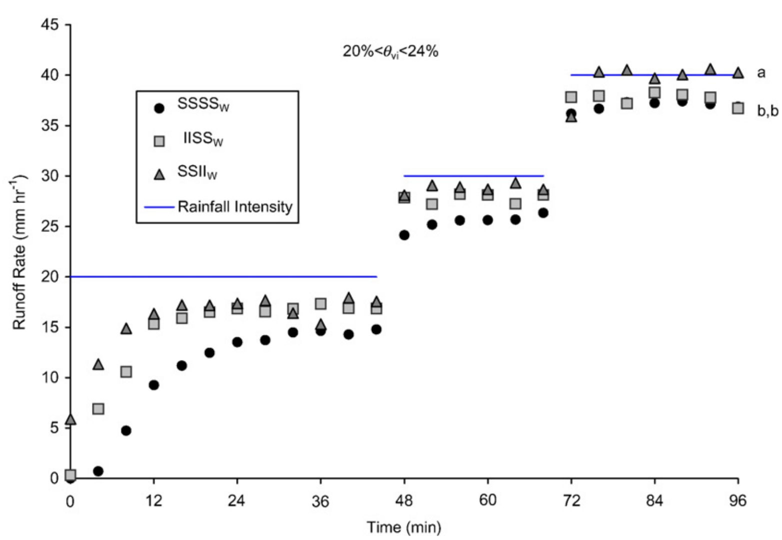

Fig. 4. Runoff rates during simulated rainfall under high initial soil moisture conditions (θ_{vi}). Ending runoff values labeled with the same lower case letter are not significantly different at $\alpha = 0.05$.

surfaces will reach the outlet only when downslope soil infiltration rate or saturation is exceeded by rainfall and run-on. As the downslope soil infiltration rate declines with time, the soil surface generates runoff more similarly to an impervious surface. Previous research has found that impervious surface impacts to hydrology are more notable during higher-frequency rainfall events having smaller peak flows than during infrequent more intense storms (Dudley et al., 2001). This further supports the finding that the most notable hydrologic differences between impervious treatments were observed in the initial stages of the rainfall simulations, when rainfall intensity was relatively low. Final runoff rates were not statistically different between impervious treatments under lower initial soil moisture conditions, but the SSII treatment did yield significantly higher final runoff rates than IISS or SSSS treatments under high initial soil moisture conditions ($\alpha = 0.05$).

3.2. Treatment impacts to erosion

3.2.1. Initial soil moisture condition impacts on soil loss flux

Since replacement of soil surface with impervious cover results in a decrease in erodible surface area, it is important to consider soil loss in terms of flux. Sediment loss flux effects of initial soil moisture condition were most evident in the upslope impervious cover treatment and least evident in the 0% impervious treatment (Figs. 5 and 6). A 4.2-fold increase in sediment loss flux was observed from $IISS_W$ as compared to $IISS_D$ during the initial 20 mm/h rainfall segment. During the subsequent rainfall segments of increasing intensity, this increase in soil loss flux diminished to 3.4 and finally to 2.3 fold. Initial volumetric soil moisture effects on sediment loss flux were less prominent for the SSII and SSSS treatments, with the wet conditions resulting in 3.0 (diminishing to 2.7) times higher sediment flux than dry conditions for SSII and 1.4 (diminishing to 1.2) times higher for SSSS. Differences decreased over the duration of the rainfall due to diminishing differences in available soil water storage capacity between initial moisture regimes.

Sediment loss steady state was not reached during the dry rainfall simulations except during the first 48-min rainfall interval at 20 mm h^{-1}, indicating that the sediment transport capacity was not reached here. Under wet initial conditions, steady state sediment loss was reached for all treatments at all rainfall intensities. For the 40 mm h^{-1} rainfall interval, $IISS_W$ soil loss flux was approximately double that of $SSSS_W$, but since $SSSS_W$ has twice the erodible surface, this translates into similar sediment loss rates (13.0 and 14.8 g min^{-1}, respectively). It is believed that this represents the sediment transport capacity of the system. The replacement of upslope soil surface ($SSSS_D$) with impervious cover ($IISS_D$) resulted in a decrease in soil loss flux under dry initial soil moisture conditions, indicating that the sediment-laden run-on was better able to detach soil particles from the surface than the clear water run-on. However, under the higher runoff rates associated with the wet initial soil moisture conditions, this effect was not observed, and in fact reversed to the point that soil loss flux differences represented similar soil loss rates, indicating that soil erosion regime had shifted from detachment limited to transport limited. In fact, $IISS_W$ final sediment loss flux was significantly greater than those of $SSSS_W$, while final $SSII_W$ sediment loss flux was significantly lower.

3.2.2. Impervious configuration impacts on soil loss flux

Plots having upslope impervious covers generated eroded sediment at approximately 3–5 times the rate of plots having downslope impervious cover. This was expected because runoff generated on upslope impervious covers would represent an erosive force to downslope soil surfaces, while runoff generated on downslope impervious cover would not contribute to on-site erosion. Spatial configuration treatment differences became more pronounced with increased duration of rainfall (Figs. 5

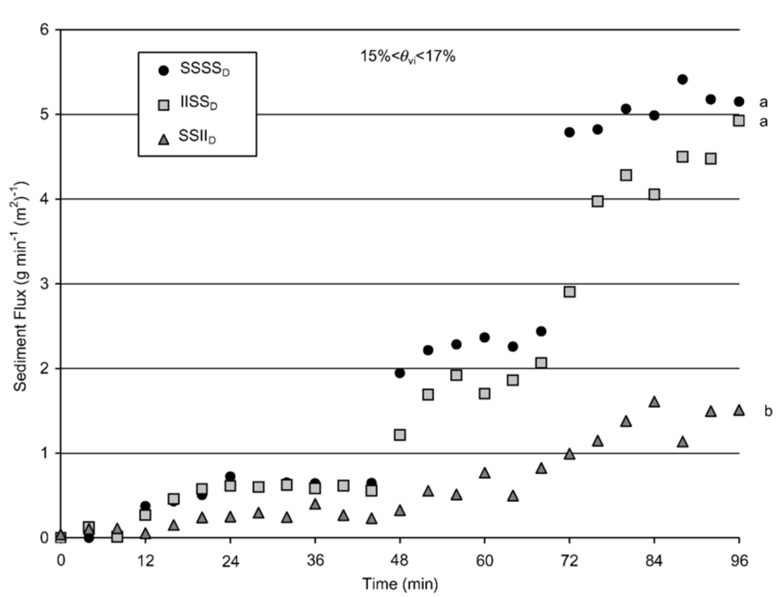

Fig. 5. Sediment loss flux during simulated rainfall under low initial soil moisture conditions (θ_{vi}). Ending sediment flux values labeled with the same lower case letter are not significantly different at $\alpha = 0.05$.

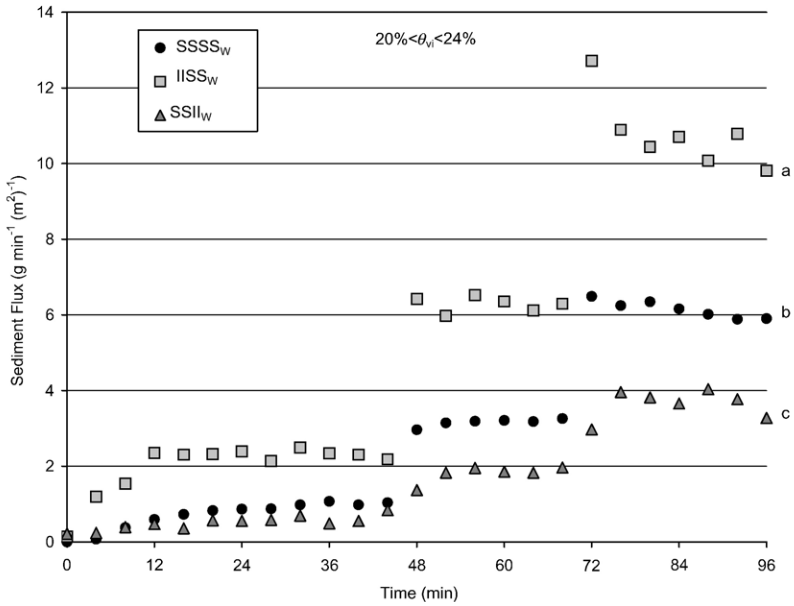

Fig. 6. Sediment loss flux during simulated rainfall under high initial soil moisture conditions (θ_{vi}). Ending sediment flux values labeled with the same lower case letter are not significantly different at $\alpha=0.05$.

and 6). This can be partly attributed to the more rapid loss of available soil water storage capacity in soil boxes receiving both precipitation and run-on from upslope impervious surfaces versus soil boxes receiving precipitation only.

Another factor contributing to impervious configuration differences is the tendency for downslope impervious surfaces to accumulate sediment from upslope soil boxes such that all of the soil lost from the upslope soil boxes was not conveyed to the outlet. Due to the short duration of the rainfall simulation, it is likely that sediment accumulation on downslope impervious surfaces did not reach equilibrium, but continued to accumulate sediment throughout the rainfall, especially where initial soil moisture conditions were dry, resulting in lower sediment losses from SSII than IISS. It is important to recognize that the erosional effects observed in this experiment represent only small scale on-site losses, and do not represent rill erosion or in-stream or downstream effects that occur beyond the outlet of the slope length or at the larger scale. For instance, the higher runoff rates observed from SSII treatments may translate into increased channel bank erosion and bed scour associated with higher flows at the larger scale.

4. Conclusions

A laboratory rainfall simulation procedure on serial soil boxes was developed and proven to be sensitive to hydrologic and erosional responses to impervious surfaces of various spatial configurations within 4-m slope sections, under small-scale sheet erosion conditions. Plots having downslope impervious surfaces (50% by area) produced initially higher runoff rates than plots having upslope impervious surfaces, but this effect was greatly dependant upon initial soil moisture. Impervious treatment did not result in sustained hydrologic differences at low initial soil moisture (15–17%), but differences in runoff rate were significant between impervious treatments under high initial moisture (20–24%), both initially at 20 mm h^{-1} rainfall, and at during the end phase of the simulation at 40 mm h^{-1}. Runoff rates were also higher overall when initial volumetric soil moisture was high versus low.

Results indicate that sloped plots having 50% upslope impervious covers generated eroded sediment at approximately 3–5 times the rate of sloped plots having 50% downslope impervious cover. The replacement of the upper 50% of the soil surface with impervious cover resulted in little change in soil loss flux when initial soil moisture was low, but resulted in a 2-fold increase in soil loss flux when initial soil moisture was high. The replacement of the lower 50% of the soil surface with impervious cover resulted in a decrease in soil loss flux. These findings suggest that impervious cover located at the upper slope end may cause more sheet erosion on the small slope scale than the same area of downslope — located impervious surface. However, since downslope impervious surfaces may result in higher runoff rates, this may have larger scale impacts to erosion not addressed in this research.

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